UHF RiverSonde Observations of Water Surface Velocity at Threemile Slough, California

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***Abstract*— A UHF RiverSonde system, operating near 350 MHz, has been in operation at Threemile Slough in central California, USA since September 2004. The water in the slough is dominated by tidal effects, with flow reversals four times a day and a peak velocity of about 0.8 m/s in each direction. Water level and water velocity are continually measured by the U. S. Geological Survey at the experiment site. The velocity is measured every 15 minutes by an ultrasonic velocity meter (UVM) which determines the water velocity from two-way acoustic propagation time-difference measurements made across the channel. The RiverSonde also measures surface velocity every 15 minutes using radar resonant backscatter techniques. Velocity and water level data are retrieved through a radio data link and a wideband internet connection.**

Over a period of several months, the radar-derived mean surface velocity has been very highly correlated with the UVM index velocity several meters below the surface, with a coefficient of determination R^2 of 0.976 and an RMS difference of less than 10 cm/s. The wind has a small but measurable effect on the velocities measured by both instruments. In addition to the mean surface velocity across the channel, the RiverSonde system provides an estimate of the cross-channel variation of the surface velocity.

Fig. 1. RiverSonde installation at Threemile Slough. The RiverSonde antenna is mounted on the left side of the walkway and is over the water about 4 m from the bank. The weather station sensors are above the antenna. The smaller antenna is for USGS data telemetry. The USGS and RiverSonde equipment are inside the shelter.

I. Introduction

A UHF RiverSonde radar system, operating near 350 MHz, has been used in several recent experiments to measure river streamflow. After several one- or two-day field tests, it was used for several months on the Cowlitz River at Castle Rock, Washington [1], in an environment where the river velocity was unidirectional with a range of 1–3.5 m/s, and the flow velocity was highly correlated with the stage height. After the conclusion of that experiment, it was moved to Threemile Slough in central California in September 2004. Threemile Slough is a 200-m wide channel which connects the Sacramento and San Joaquin Rivers, and the fresh-water flow in the slough is dominated by tidal effects, with flow reversals four times a day and a peak velocity of about 0.8 m/s in each direction. Water level and water velocity are continually measured by the U. S. Geological Survey at Threemile Slough and are relayed through a radio data link. The Threemile Slough site is attractive because of the long-term *in-situ* instrumentation, and because the 200-m width of the channel provides an opportunity to test the RiverSonde operation at a greater range than had been available previously. In contrast to the Cowlitz River site, the velocity and stage height are in nearly phase quadrature at Threemile Slough because of the dominating tidal influence.

II. Threemile Slough Experiment

The Threemile Slough site is shown in Fig. 1. The RiverSonde antenna is mounted on the walkway, with the antenna over the water about 4 m from the bank. A weather station, measuring wind speed and direction, temperature, humidity and rainfall, is mounted directly above the RiverSonde antenna, with the anemometer about 8 m above the water surface. Water height, referred to as stage, is measured using a stilling-well and float directly beneath the housing shown in the figure. The water velocity is continually monitored by an *in-situ* ultrasonic velocity meter (UVM) just to the left of the shelter in Fig. 1. The UVM determines the water velocity from two-way acoustic propagation time-difference measurements made between two sensors on opposite sides of the channel at an

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
25 JUL 2005	**N/A**	**-**

4. TITLE AND SUBTITLE
UHF RiverSonde Observations of Water Surface Velocity at Threemile Slough, California

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
CODAR Ocean Sensors, Ltd. 1914 Plymouth Street Mountain View, CA 94043 USA

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM001850, 2005 IEEE International Geoscience and Remote Sensing Symposium Proceedings (25th) (IGARSS 2005) Held in Seoul, Korea on 25-29 July 2005. , The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**UU**	**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

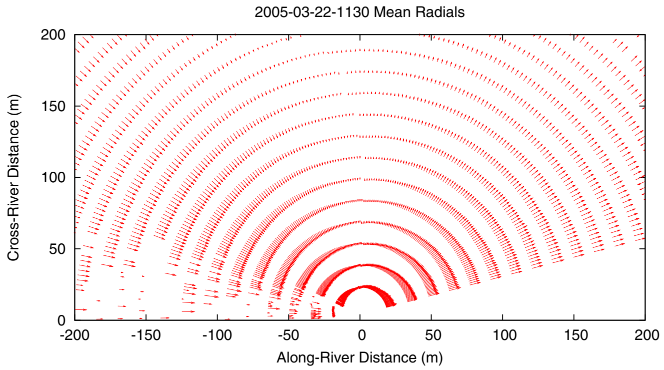

Fig. 2. Radial flow vectors averaged over 15 minutes on 22 March 2005 at 11:30 PST at Threemile Slough. Vectors are plotted between the river banks with 1° resolution in angle and 15 m in range. A velocity of 1.0 m/s is plotted with an equivalent length of 10 m. The mean direction of flow is aligned with the horizontal axis, with north toward the left. The broadside direction of the antenna is about 12°counterclockwise from the perpendicular direction to the bank, and the sharp angular cutoff at the right side of the plot is due to antenna hardware and data processing limitations.

angle of approximately 45° from the mean flow direction. The UVM path is within the field of view of the radar system. The water depth in the channel typically is about 7 m, and the UVM transducers are about 2.4 m above the bottom of the channel. The UVM measurement is an index velocity that is indicative of the velocity a few meters below the surface, although not necessarily at the exact height of the acoustic sensors. At the experiment site, the channel runs almost directly north-south.

The RiverSonde installation is similar to that at Castle Rock [1], with the radar antenna looking broadly across the channel with an angular field of view of nearly 180°. The antenna consists of three yagi antennas, and MUSIC direction finding [2] is used to determine the angle of arrival of echo energy with a resolution of 1°. Because of the 200-m width of the channel, a range resolution of 15 m is used, and because of the dynamics of the tidal motion, radar estimates of the water velocity are made every 15 minutes. Data processing is done on-site using a small laptop computer, and data are available through a wideband internet connection. In contrast with the UVM measurement, the radar measurement represents the velocity within the top 3 or 4 cm of the surface, at an effective depth of about 8% of the resonant water wavelength [3], [4]. As is shown below, the two instruments see essentially the same tidally-driven component of the velocity, but there are effects due to the wind which are seen more strongly in the radar signal.

III. Data Processing

After the radar echoes are separated into range and Doppler bins, a radial vector map is constructed by averaging data over 15 minutes. An example of average radial vectors is shown in Fig. 2, for a portion of the tidal cycle in which the flow is toward the south. From the radial vectors, an estimate of the along-channel velocity as a function of distance across the channel is made using two techniques. The first technique consists of defining several strips 5 m wide, aligned in the direction of flow, and fitting a single velocity vector to all of the radial vectors falling within that strip. Typically there are 9 individual data segments covering each 15-minute interval, and both the mean and median of estimates over the 9 data sets are calculated for each position. An example is shown in Fig. 3a for the data set of Fig. 2, with the medians of the estimates shown as asterisks and the mean and standard deviations shown with boxes and error bars. Generally the medians are more stable than the means, so the medians are used for the subsequent processing. The second technique for estimating the velocity profile consists of looking in symmetrical directions ±15, 20, ..., 45° from the broadside direction and 5° wide, and fitting an along-channel velocity vector to radial vectors falling within those directions. An example of the profile calculated by the second technique is

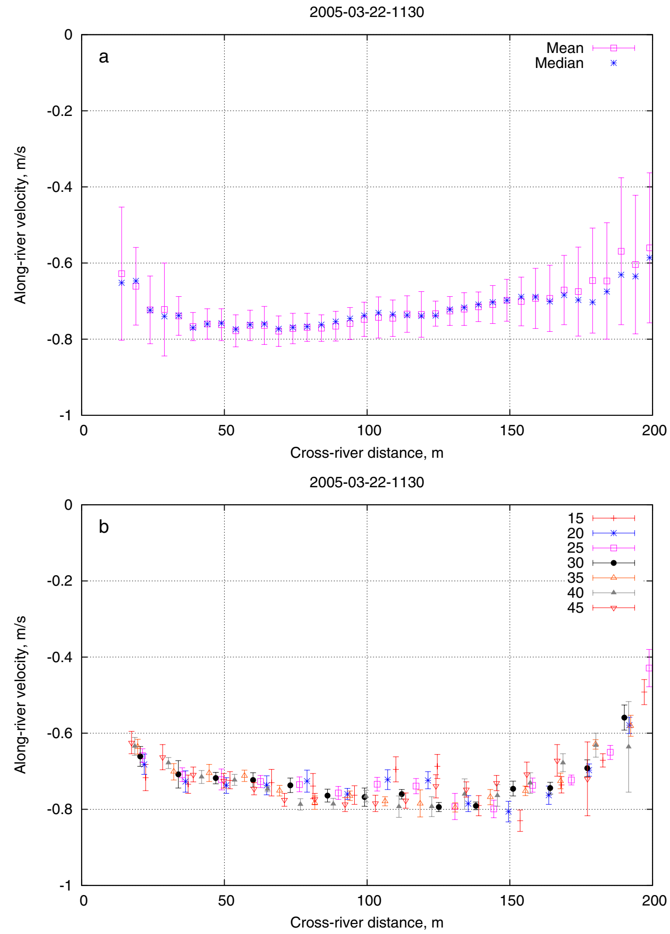

Fig. 3. Along-channel RiverSonde velocity *vs* distance across the channel for 22 March 2005 at 11:30 at Threemile Slough. The distance origin is at the radar antenna, and positive velocity represents flow toward the north. The blue asterisks show the median of 9 measurements taken over a 15-minute interval, and the red symbols show the sample means and standard deviations of the same measurements. (a) Profile calculated by fitting a vector to all the radials falling within a 5-m strip parallel to the flow direction. Velocity estimates are made every 5 m across the 200-m wide channel. (b) Profile calculated by combining radial vectors in 5°sectors symmetrically displaced from the perpendicular to the flow direction.

TABLE I
MAJOR TIDAL AND WIND COEFFICIENTS.

Component	Frequency (c/h)	RiverSonde	UVM
w_e		-0.0039	-0.0013
w_n		0.0102	-0.0042
M_2	0.08051	0.7010	0.7218
K_1	0.04178	0.3191	0.3295
O_1	0.03873	0.1985	0.2049
N_2	0.07900	0.1327	0.1417
S_2	0.08333	0.1286	0.1378
MO_3	0.11924	0.1158	0.1138
K_2	0.08356	0.0879	0.0878
MK_3	0.12229	0.0865	0.0861
P_1	0.04155	0.0788	0.0801
L_2	0.08202	0.0670	0.0644

shown in Fig. 3b. The two techniques give similar results.

Once the velocity profiles are calculated, a single along-channel average velocity is estimated by taking the median of the individual median velocity profile estimates from 40 to 120 m from the near shore, for which signals are almost always available and which represent flow near the center of the channel. A plot of an 8-day time series of RiverSonde velocity estimates along with UVM measurements and wind vectors is shown in Fig. 4. The UVM measurements are shown as the solid blue curve, and the radar estimates, along with their sample standard deviations, are shown with the red points and bars. The wind vectors are shown along the top, with a line vertically upward indicating wind blowing toward the north along the channel, in the direction of positive water velocity.

The agreement between the radar and UVM measurements is immediately apparent. While it is clear that the radar and UVM measurements track each other very closely, it also appears that strong wind also has a noticeable effect, for example the two high-wind events on 19 and 22 March, where the radar velocity is clearly displaced upward with respect to the UVM velocity. (The channel runs almost directly north-south at the site, and the wind toward the northwest is nearly in the direction of the channel.) A linear regression of radar estimates on the UVM measurements and the northward and eastward components of the wind gives $v_r = -0.009 + 0.937 v_u - 0.002 w_e + 0.015 w_n$ where v_r is the RiverSonde velocity, v_u is the UVM acoustic velocity, w_e is the eastward wind at the anemometer (about 8 m above the water surface) and w_n is the northward wind, with a coefficient of determination R^2 of 0.976 and an RMS difference of 0.093 m/s. The regression was applied to 7985 data points covering 83 days. Note that this regression compares the radar and UVM velocities, but does not necessarily describe the effect of the wind on each velocity individually.

In order to further examine the influence of the wind on the two instruments, a linear regression analysis was performed on the radar and UVM velocities individually (using the Regress function of Mathematica). The regression functions included the northward and eastward components of the wind and the 38 tidal components listed in Table 1 of [5]. The regression coefficients for the wind and the 10 tidal components representing 98% of the total energy are shown in Table I, which shows the components and their frequencies in cycles/hour and the magnitudes of the coefficients. The coefficients for the tidal components are similar between the two instruments and are consistent with the simple regression of v_r on v_u and the wind above. The difference in the coefficients between radar and UVM for the northward wind is approximately the same as that based on a regression of radar against the UVM and wind directly $(0.0102 - (-.0042)\ vs\ 0.015)$. However, it appears that there is a small effect of the wind on the UVM velocity several meters below the surface, although in a direction opposing the wind. The reason for the reversed direction is not clear.

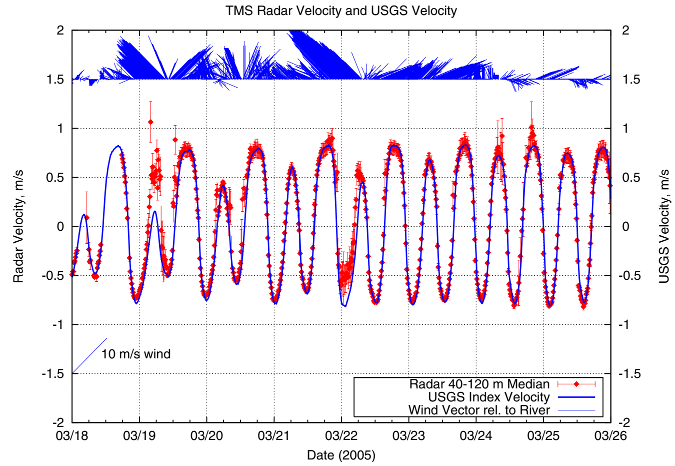

Fig. 4. Time series of mean water velocity inferred from the RiverSonde measurements (red) and from in-situ ultrasonic velocity meter measurements (blue curve) for the period 18 March 2005 to 26 March 2005. Wind vectors are shown at the top, with a vector vertically upward representing wind blowing toward the north (in the positive water velocity direction). The radar error bars indicate one standard deviation of 9 individual measurements for each 15-minute interval.

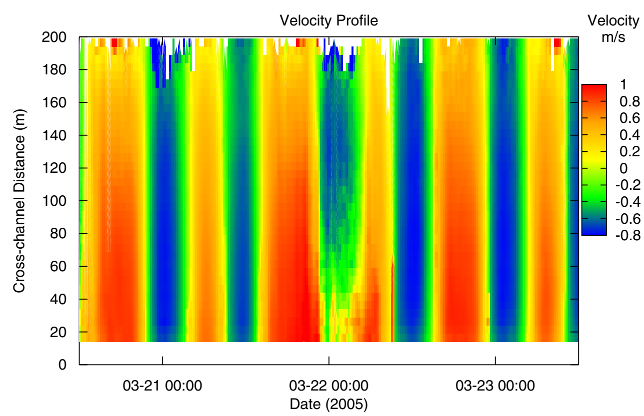

Fig. 5. Time series of along-channel velocity from 12:00 on 20 March to 12:00 on 24 March 2005.. The horizontal axis is time, and the vertical axis is distance across the channel. The velocity is indicated by the color bar on the right. The regular pattern of vertical stripes is the result of tidal forcing, while the effect of the high wind on 22 March can be seen as a shift in the velocity toward positive (northward-flowing) values.

There is additional information in the radar data beyond the

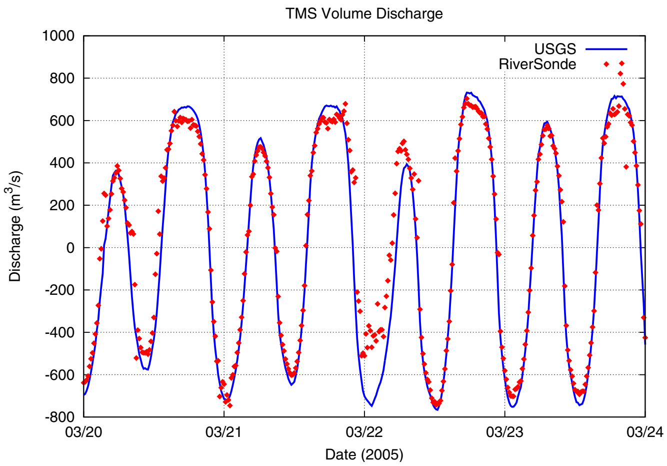

Fig. 6. Time series of total discharge volume from 20 March to 24 March 2005. The discharge estimated by the USGS from the UVM index velocity and stage height is shown in the solid blue curve, and the discharge estimated from the RiverSonde surface velocity combined with bottom profile and stage height is indicated by the red dots. The deviation between the two estimates on 22 March is a result of high winds on that day.

velocity averaged across the channel. Velocity profiles similar to Fig. 3 are computed every 15 minutes. Fig. 5 shows the variation in the velocity profile across the channel as a function of time for 4 days starting at 12:00 on 20 March 2005. Time runs horizontally across the figure, distance across the channel runs vertically, and the along-channel velocity is depicted by the color as indicated by the color bar. The periodic tidal signature dominates the figure, but the effect of the high wind on 22 March is also evident. The perturbation in the velocity is higher on the side of the channel near the radar than on the far side. This is consistent with the direction of the wind toward the northwest, as indicated in Fig. 4, since the fetch would be greater on the near side of the channel for wind in that direction, and the far side might be slightly sheltered. For the other cycles, when the wind was low, there is a slight decrease in the magnitude of the surface velocity near the far bank. The effective range resolution of the radar is about 21 m, due to a Hamming window applied to the basic 15-m range cell, so a rapid variation in velocity over a few meters very close to either bank would be difficult to resolve.

Finally, the total water discharge volume was estimated from the RiverSonde measurements. On 8 March 2005, *in-situ* acoustic instruments attached to a small boat were used to measure the bottom profile of the channel at intervals of a few cm across the channel. The stage height at the time of this snapshot was noted, and the cross-sectional area for other times was estimated by combining this profile with the instantaneous *in-situ* stage height data. The volume discharge was computed by interpolating both the velocity profile obtained from the RiverSonde measurements and the cross-sectional area estimates to 1-m intervals and then integrating their product across the channel. The RiverSonde surface velocity was multiplied by 0.85 to obtain an estimate of the velocity averaged over depth. The factor of 0.85 has been observed in many experiments using acoustic instruments to relate the depth-averaged velocity to the surface velocity [6]. An example of the discharge for the period 20–24 March 2005 is shown in Fig. 6 which compares the discharge estimated from the RiverSonde and UVM measurements. A linear regression analysis on 383 estimates every 15 minutes for the 4-day period gives $Q_r = 50.37 + 0.908Q_u$ m^3/s, where Q_r is the RiverSonde discharge volume estimate and Q_u is the discharge volume estimate from the UVM data, with a coefficient of determination $R^2 = 0.956$. There was no attempt to remove the effect of the high wind event on 22 March which can be seen in Figs. 4 and 6.

IV. Summary

The operation at Threemile Slough has provided a unique long-term comparison of *in-situ* UVM velocity measurements several meters below the water surface and wind measurements approximately 8 m above the water with the non-contact RiverSonde velocity measurements in the top 3–4 cm of the water surface. Measurements taken every 15 minutes over a 3-month period indicate a very high correlation between the two instruments, with a coefficient of determination R^2 of 0.976. The surface velocity estimates can be combined with stage height data to obtain a good estimate of the discharge volume. The surface velocity appears to respond to the wind with about 1.0% of the wind speed at 8 m height, and at this site that appears to represent an increase of about 1.5% of the wind speed when compared to the UVM velocity at depth. The RiverSonde is still in operation at this site at the time of this writing, and additional *in-situ* acoustic instruments are expected to be installed.

Acknowledgment

The authors acknowledge the support of the Hydro-21 Committee of the U. S. Geological Survey and RD Instruments for help in planning and conducting the experiment.

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